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JGOFS

JOINT GLOBAL OCEAN FLUX STUDY

A Core Project of the International Geosphere-Biosphere Programme

JGOFS REPORT No. 35

REPORT of the INDIAN OCEAN SYNTHESIS GROUP on the ARABIAN SEA PROCESS STUDY

SCIENTIFIC COMMITTEE ON OCEANIC RESEARCH

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CONTENTS

2. SPECIFIC TOPICS

2.1 The Surface Circulation of the Northern Arabian Sea

John C. Kindle

Oceanography Division, Naval Research Laboratory
Stennis Space Center, MS 39529-5004
USA

Introduction

Prior to the Arabian Sea Expedition of 1994-1995, our understanding of the northern Arabian Sea's response to the seasonally reversing monsoon cycle was based on climatological ship drift reports (Cutler and Swallow, 1984). Although occasional expeditions to the region provided new insights (*e.g.*, Elliot and Savidge, 1990; Bauer *et al.*, 1991) an integrated understanding of the mesoscale response to the monsoon cycle relative to the mean seasonal circulation was lacking. That the best estimates of the surface forcing resulted from monthly composites of ship wind observations complicated the efforts to understand this highly variable region. Hence, it is not surprising that prominent among the recent discoveries are 1) the pronounced spatial and temporal structure of the monsoon atmospheric forcing and 2) the importance of mesoscale variability in the associated ocean response. Among the important mesoscale features are coastal jets and filaments along the Oman coast during the Southwest (SW) Monsoon that are capable of exporting nutrient rich upwelled water hundreds of kilometres offshore. This paper reviews observational and modelling studies of the seasonal response of the northern Arabian Sea circulation to the monsoon cycle with a focus on results from the Joint Global Ocean Flux Study (JGOFS) Arabian Sea Expedition of 1994-95. Emphasis is placed on the circulation features north of approximately 10°N. An excellent review of the basin-wide circulation features, including results from the World Ocean Circulation Experiment (WOCE) efforts of 1994-96 can be found the recent article by Schott and McCreary (2001).

Atmospheric Forcing

The basin-scale circulation of the Arabian Sea is governed by the response to a seasonally reversing monsoon cycle, characterised by upwelling-favourable, south-westerly winds during the SW Monsoon, reversing to north-easterly (albeit weaker) winds during the Northeast (NE) Monsoon. Meteorological measurements from a moored array centred at approximately 15.5°N, 61.5°E and deployed from October 1994 to October 1995, provide the first high frequency (*i.e.*, sub-monthly) direct observations of the monsoon cycle in the interior of the Arabian Sea (Rudnick *et al.*, 1997; Weller *et al.*, 1998). Based on these measurements, the four seasons for the 1994-95 monsoon year were defined as: September 16 to October 31 for the Fall Intermonsoon; November 1 to February 15 for the NE Monsoon; February 16 to May 31 for the Spring Intermonsoon and June 1 to September 15 for the SW Monsoon. The excellent agreement between these observations and results from operational atmospheric prediction models (Weller *et al.*, 1998) (**Figure 1**) suggest that the atmospheric models may be used to describe the essential characteristics of the spatial and temporal variability of the of the atmospheric forcing throughout the basin. Likewise, Halpern *et al.*, (1998) discovered excellent agreement between the observed winds from the mooring and the satellite-derived winds from the ERS-1 scatterometer.

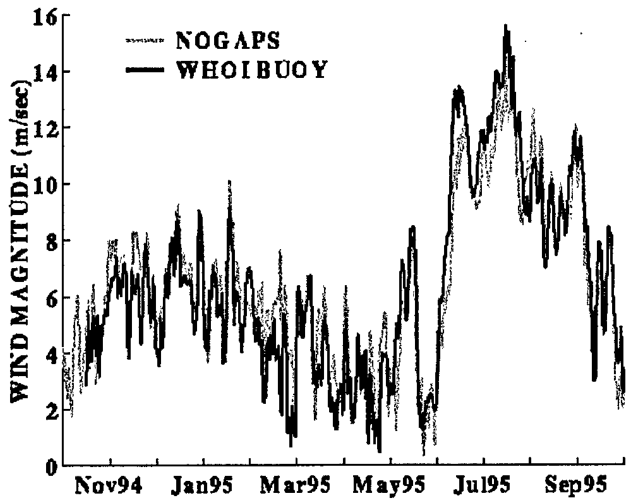

Figure 1. Time-series of observed wind magnitude (dark line) versus atmospheric model winds (light line) at 15.5°N, 61.5°E for the period October 1994 to October 1995. The atmospheric model winds are from the U.S. Navy's Operational Global Atmospheric Prediction System (NOGAPS).

Both the atmospheric model winds (Weller *et al.*, 1998) and the satellite-derived winds (Halpern *et al.*, 1998) reveal significant regional differences in the timing of the onset and relaxation of the winds within a season. For example, Weller *et al.*, (1998) used the operational wind product from the U.S. Navy to reveal a 7-10 day delayed onset of the 1995 SW Monsoon at the mooring site, whereas the onset near the Oman coast occurred normally. However, it should be noted that upwelling-favourable winds along the coast of Oman generally begin in April-May (Weller *et al.*, 1998), even prior to the reversal of the winds in the interior of the Arabian Sea. This is consistent with the analysis of ship reports by Fieux and Stommel (1977) indicating that the onset of upwelling-favourable winds along the Oman coast may begin in April. While the winds along the Oman coast in April-May are not as strong as during the SW Monsoon period, they appear to be sufficient to generate a coastal upwelling response as detected in AVHRR imagery (Rixen *et al.*, 1996; Arnone *et al.*, 2001). The potential roles of this weak-to-moderate coastal upwelling during April-May in setting the stage for the physical and biogeochemical responses to the primary SW Monsoon onset in June warrant further study.

Ocean Response to the Monsoon Cycle

The Southwest Monsoon

Historical ship drift records show the existence of the Oman Coastal Current (OCC) north of approximately 14°N by early May (Cutler and Swallow, 1984). In their analysis of the ship drift records, Elliot and Savidge (1990) showed a north-eastward flowing OCC of around 0.4 m sec^{-1} in magnitude and extending to 200 km offshore during the SW Monsoon. The current turned abruptly to the east off Ras al Hadd (**Figure 2**). However, direct measurements of the coastal flow from ADCP instruments during this season in 1987 showed that the north-eastward coastal flow weakened toward the southwest from an estimated transport of ~10 Sv. near Ras al Hadd to weak and variable flow at ~ 17°N-18°N (Elliot and Savidge, 1990). Additionally, the ADCP data analysed by Flagg and Kim (1998) for the 1995 SW Monsoon displayed no mean coastal current

to the northeast, but rather the presence of variable flow characterised by current reversals over relatively small distances. Flagg and Kim (1998) hypothesised that the differences between the direct observations of the OCC and the historical ship drift data may be accounted for by a systematic bias in the ship observations due to the persistent nature of the high winds and sea-state during this period. Clearly, questions remain about the nature of the Oman Coastal Current: During the SW Monsoon, is the OCC comprised of several distinct flows of limited alongshore extent or does it exist in the mean but disrupted by the pronounced mesoscale variability? Moreover, while we know the fate of the coastal flow after it leaves the coast at Ras al Hadd, we know little of its origins. The southeastern-most extent of the OCC has not been documented.

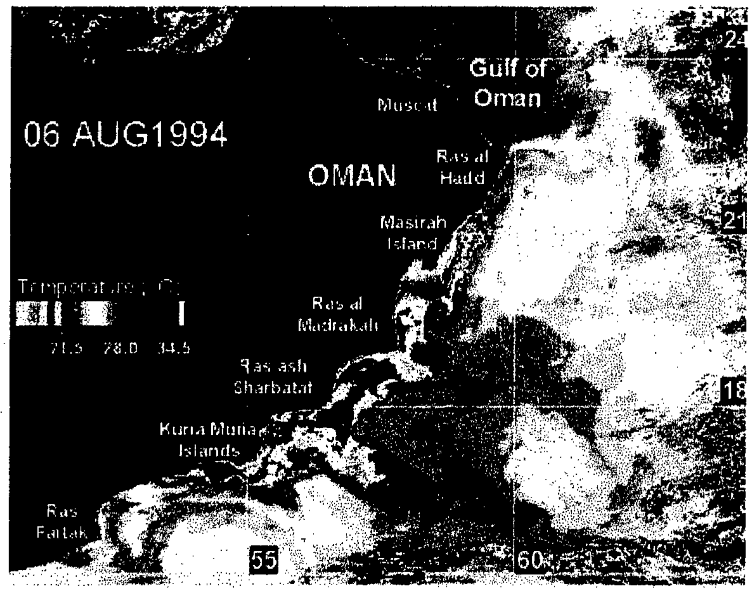

Figure 2. AVHRR image from 06 August 1994 showing major filaments extending offshore from Ras ash Sharbatat, Ras al Madrakah and Ras al Hadd (Image courtesy of R. Arnone).

Among the most prominent SW Monsoon features along the Oman coast are filaments and jets (**Figure 2**) which are capable of exporting cool, nutrient rich, upwelled coastal waters hundreds of kilometres offshore (Young and Kindle, 1994; Brink *et al.*, 1998). The first direct measurements of these features were described by Elliot and Savidge (1990) who discovered plumes of cold water extending offshore from the coast in the region between Ras ash Sharbatat and Ras al Madrakah. This is in approximately the same region as a major filament that was observed during the 1995 SW Monsoon (Brink *et al.*, 1998; Flagg and Kim, 1998; Arnone *et al.*, 2000; Lee *et al.*, 2000; and Manghnani *et al.*, 1998). Some properties of the filaments have been described as similar to those off the U.S. Pacific west coast (Elliot and Savidge, 1990; Brink *et al.*, 1998). However, Flagg and Kim (1998) view the offshore-directed plumes as part of a major anticyclonic feature that remains essentially in place for approximately six months, thereby extending through the SW Monsoon into the winter season. Manghnani *et al.* (1998) hypothesised that the plume was not part of the offshore deflection of the coastal current, but rather resulted from an interaction between the wind field and anticyclonic mesoscale features that may have existed prior to the onset of the SW Monsoon.

When the Oman Coastal Current reaches Ras al Hadd, the flow turns offshore to the northeast and east to form the Ras al Hadd Jet (**Figure 2**). This feature is also referred to as the Ras al Hadd Front because it forms the seasonal boundary between the northern Arabian Sea and the Gulf of Oman. The measurements of Elliot and Savidge (1990) of the OCC just prior to reaching

Ras al Hadd, revealed a transport of ~ 10 Sv. within 100 km off the coast. Flagg and Kim (1998) discovered that the Ras al Hadd Jet intensified in August 1995 following the reversal of the flow along the northeastern Oman coast from northward to southward, thereby adding to the flow along the Ras al Hadd Front. They speculated that the reversal of the flow along the northeastern Oman coast in August was related to the intensification and/or propagation of a cyclonic eddy in the Gulf of Oman during this period. Similarly, Baker *et al.*, (1996) suggested that such an eddy plays a role in the dynamics of the Ras al Hadd Jet: They hypothesize that the OCC at Ras al Hadd forms a double vortex as it extends offshore during the Fall Intermonsoon period. It is speculated that to the south, an anticyclonic vortex (or eddy) forms while to the north, in the Gulf of Oman, a cyclonic eddy forms, both of which are driven by the extension of the Ras al Hadd Jet into open waters. Böhm *et al.* (1999) provided an extensive description of the Ras al Hadd Jet and the associated cyclonic and anticyclonic eddies based on ADCP measurements and remotely sensed observations in 1994 and 1995. They estimated that the transport of the jet varied from 2-8 Sv. in magnitude and exhibited a maximum flow in September. Böhm *et al.* (1999) suggested that, while the counter-rotating eddies may interact with the jet, they may not necessarily be generated by this feature. The relationship(s) between the Ras al Hadd Jet and the respective anticyclonic and cyclonic eddies to the south and north deserves further attention.

Among the key results of the ADCP analysis by Flagg and Kim (1998) is that the eddy kinetic energy (EKE) in the northern Arabian Sea dominates that of the mean and is enhanced in the near coastal region. In an extension of the ADCP-based study, Kim *et al.* (2001) utilised satellite-derived sea level anomalies from the TOPEX/Poseidon altimeter to provide additional analyses of the EKE properties in the northern Arabian Sea. The results were in agreement with the ADCP study in affirming the importance of eddy activity in this region. The seasonal variation of EKE was such that it increased in magnitude and areal extent during the SW Monsoon. Horizontal scales of the eddies varied from ~200-500 km nearshore to ~100-200 km in the interior. Interestingly, they also discovered that the primary area of reduced eddy presence coincided with the core of the Oxygen Minimum Zone (OMZ). Furthermore, the study revealed that eddy activity within the Arabian Sea basin was confined primarily to the region north of 15°N. The generating mechanisms for the eddy field remain to be determined.

The behaviour of the surface mixed-layer during this season was addressed in both observational and modelling studies. Lee *et al.*, (2000) used high-resolution observations from a towed profiler during 1994 and 1995, as well as climatological records of surface forcing and mixed-layer depths, to examine the seasonal behaviour of the surface mixed-layer in the northern Arabian Sea. Their analysis suggests that during the SW Monsoon, the shallow mixed-layer inshore of the wind maximum is maintained by a balance between wind-driven entrainment and the combined effects of horizontal advection and Ekman pumping. Offshore of the wind maximum, Lee *et al.*, (2000) show that Ekman pumping and wind-driven entrainment act together to deepen the mixed-layer with minimal influence from horizontal advection. Fischer (2000) utilised data from the Woods Hole Oceanographic Institute (WHOI) mooring at ~15.5°N, 61.5°E, a location that was chosen to approximately coincide with the climatological axis of the wind stress maximum during the SW Monsoon, and a three-dimensional model to examine the mixed-layer response during this season. His results indicated that, at this location, local forcing dominated the mixed-layer response except during the latter stages of the SW Monsoon, when horizontal advection played an important role. Similarly, Rochford *et al.*, (2000), in a modelling study using a three-dimensional numerical model forced by 12-hourly atmospheric model winds, suggested that local forcing dominated the mixed-layer response at the mooring site during the first half of the SW Monsoon, but horizontal advection was also an important component during the second half of the summer (SW) Monsoon period. Finally, the modelling studies of Fischer (2000) and McCreary *et al.* (2000) found that rectification to the diurnally forced signal needs to

be included to produce the most realistic mixed-layer response. This is particularly true for coupled bio-physical models attempting to simulate the seasonal surface chlorophyll distribution in the interior of the northern Arabian Sea (McCreary *et al.*, 2000).

The Fall Intermonsoon

Prominent features along the Oman coast generated during the SW Monsoon tend to linger in place during the Fall Intermonsoon, as noted above for the cyclonic and anticyclonic eddies associated with the Ras al Had Jet (Arnone *et al.*, 2001). Flagg and Kim (1998) noted the continued presence of the Ras al Hadd Jet, which appeared to maintain its intensity during the Fall Intermonsoon period due to the intensification of the southward flow along the northeast coast of Oman. Shi *et al.* (2000) reported that the cold surface water upwelled during the SW Monsoon lingered for nearly a month following the end of the monsoon in bays along the Oman coast.

The Northeast Monsoon

The transition from the Fall Intermonsoon to the NE (winter) Monsoon occurs in November. In the northern Arabian Sea, the primary circulation response to the onset of the northeasterly winds is the reversal of the Oman Coastal Current to southeastward flow, thereby yielding a continuous southward current that extends along the northeast coast of Oman, turns the corner at Ras al Hadd and continues southward along the coast until it is entrained into offshore directed squirts and jets south of ~ 20°N (Flagg and Kim (1998). Anticyclonic features that were once directly connected to the coastal circulation during the SW Monsoon and Fall Intermonsoon periods evolve into separated eddies that exhibit a tendency to propagate southward along the coast and may occasionally directly impact the coastal circulation. Along the northeast coast of Oman, the southward flow decays and reverses to weak northward flow that persists from January to July (Flagg and Kim, 1998).

The mixed-layer behaviour during the NE Monsoon is characterized by increased deepening with distance offshore and is dominated by convective overturning (Lee *et al.*, 2000). This is consistent with the earlier work of Weller *et al.*, (1998) who utilised observations from the WHOI mooring to demonstrate the importance of convective overturning to the mixed-layer response in the central Arabian Sea during this season. Wiggert *et al.* (2000) used observations from the mooring and a one-dimensional coupled bio-physical model to show the importance of diurnal forcing to the surface chlorophyll *a* distributions. They also hypothesised that the interannual variation of this mechanism may be an important factor in the observed interannual variability of chlorophyll *a* distributions during this monsoon season. Such interannual variability was also examined by Kumar *et al.* (2001) who discovered deeper mixed-layer depths, colder SST values and elevated chlorophyll concentrations during the NE Monsoon of 1997 relative to that of 1995.

Recommendations

1. To perform retrospective synthesis studies that combine *in situ* and remotely sensed data together with data-assimilative model simulations capable of representing observed features during the Arabian Sea Expedition of 1994-95. Such simulations would be able to significantly aid the investigation of the relative importance of physical forcing mechanisms governing the biological response during the monsoon cycle. For example, such studies are needed to help interpret the statistical relationships between the sediment flux measurements and surface forcing.

2. To conduct additional field work just prior to and following the onset of the SW Monsoon to investigate such features as 1) the role of the upwelling along the Oman coast during April-May prior to the onset of the SW Monsoon, 2) the generating mechanisms for the pronounced filaments observed during the SW Monsoon with a focus on examining the role(s) of pre-existing coastal features in the development of coastal jets and filaments, 3) the intriguing hypothesis of the role(s) diapausing copepods play in the timing of diatom blooms relative to the onset of the SW Monsoon.

3. To conduct additional fieldwork during the NE Monsoon to better understand and to test emerging hypotheses to explain the pronounced interannual variation of phytoplankton blooms during this season.